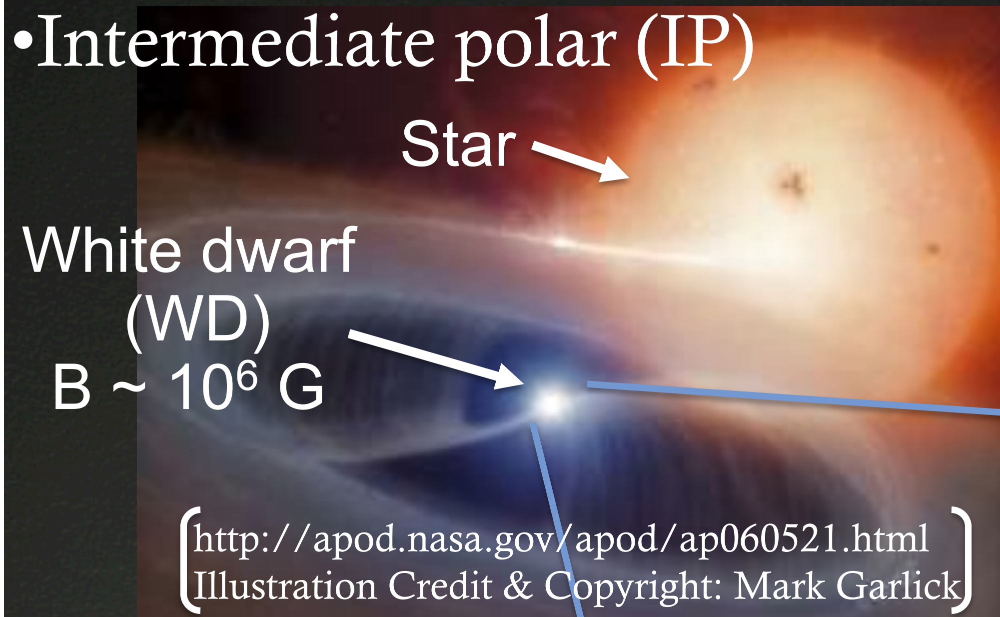
Suzaku observation of the eclipsing intermediate polar EX Hydrae

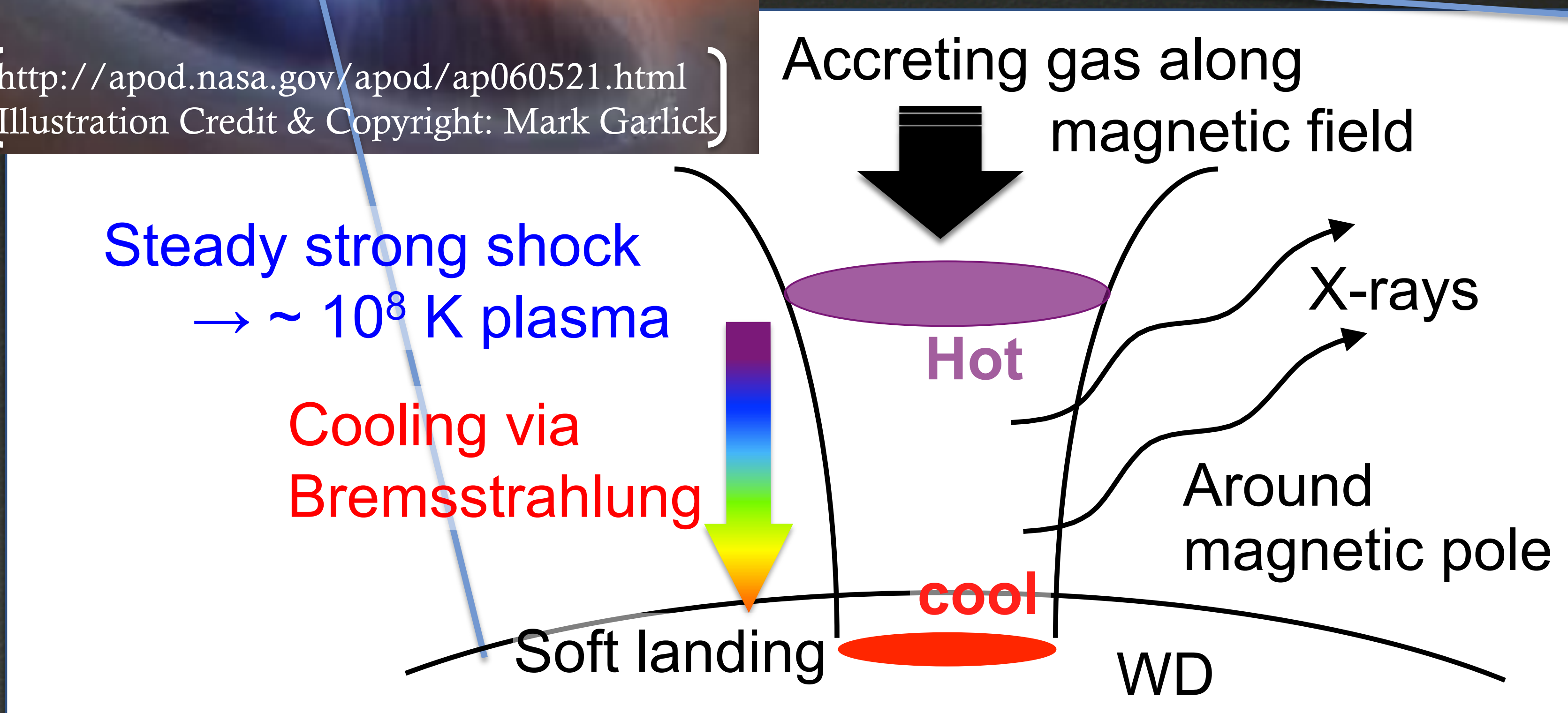
Takayuki Hayashi, Manabu Ishida
(ISAS/JAXA, Tokyo Metropolitan Univ.)
Yukikatsu Terada (Saitama Univ.)
and Aya Bamba (Aoyama Univ.)

Accretion column in IP

- Intermediate polar (IP)



- Accretion column (Today's standard)



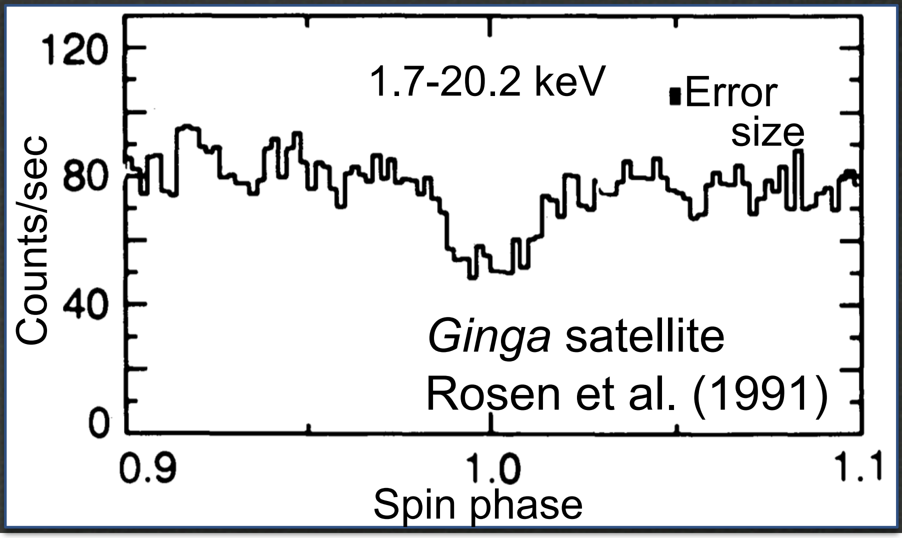
Intermediate polar EX Hydrae

P_{spin} = 4022 sec (Mauche et al. 2009)
P_{orb} = 5895 sec (Mumford 1967)
D = 64.5 pc (Beuermann et al. 2003)
M_{WD} = 0.48 $M_\odot$ (X-ray line ratio, Fujimoto&Ishida 1997)
= 0.42 $M_\odot$ (X-ray, Yuasa et al. 2010)
= 0.79 $M_\odot$ (Opt&IR, Beuermann & Reinsch 2008)
$L = 5.8\times10^{31}$ ergs sec^{-1} (Pekon & Balman 2010)

cf. typical IP V1223 Sagittarii
: $L = 1.3\times10^{34}$ ergs sec^{-1} (Hayashi et al. 2011)
→ EX Hydrae is low accretion rate

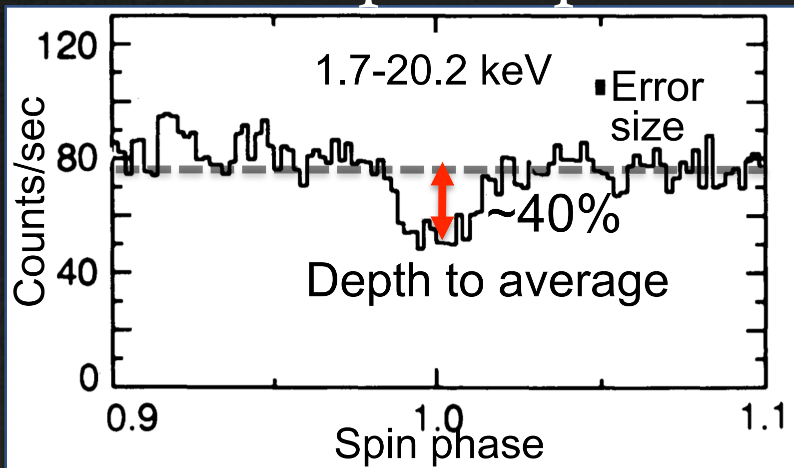
I = 77.8 deg (Opt&IR, Beuermann & Reinsch 2008)

X-ray partial eclipse
(Detail in next slide)

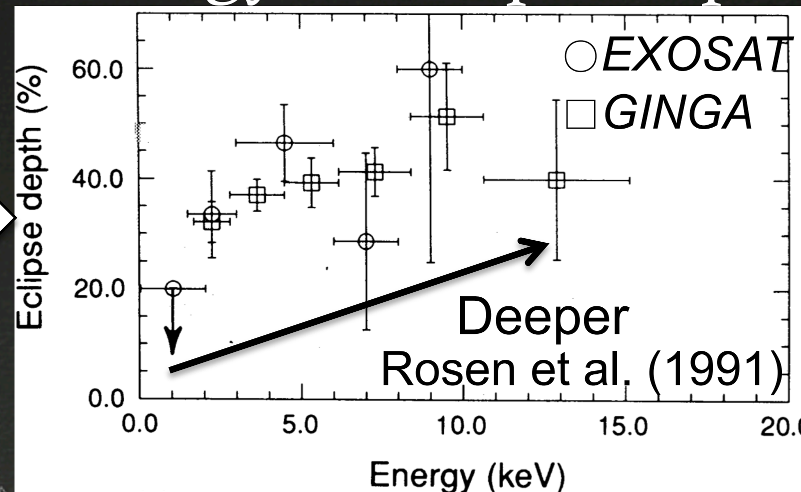


Partial eclipse

• Partial eclipse depth



• Energy vs Eclipse depth



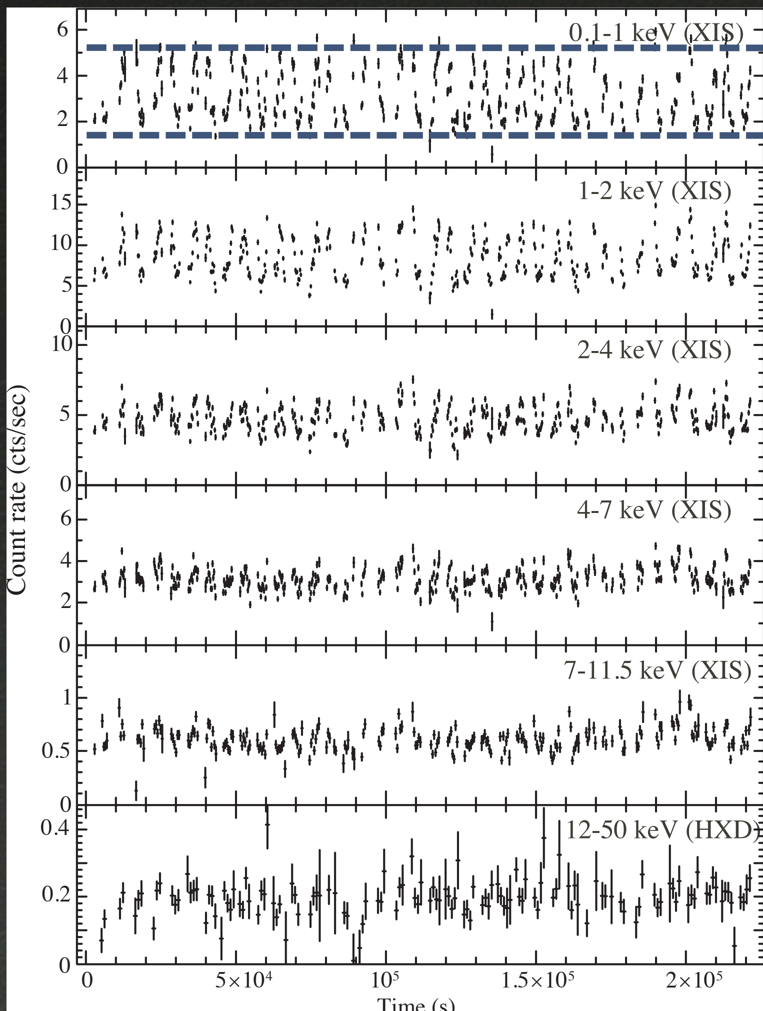
Partial eclipse
→ Can extract a part of accretion column information
→ Good target for accretion column investigation in low accretion system

Rosen et al. (1988)
Ishida et al. (1994)

Suzaku observation

2007 Jul 18th-21th

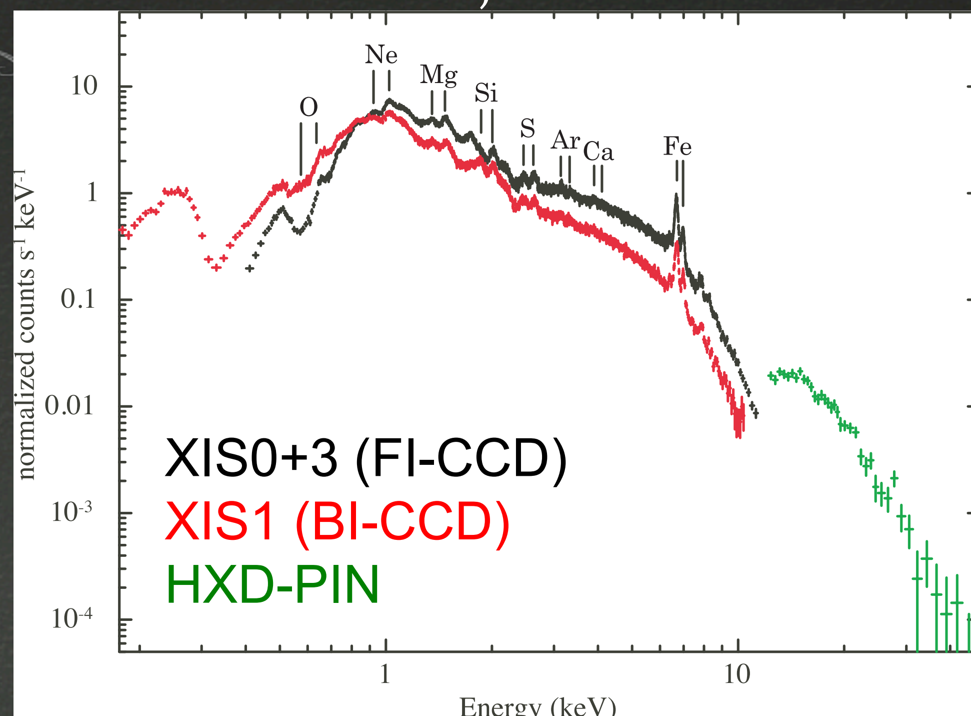
•Normalized light curve



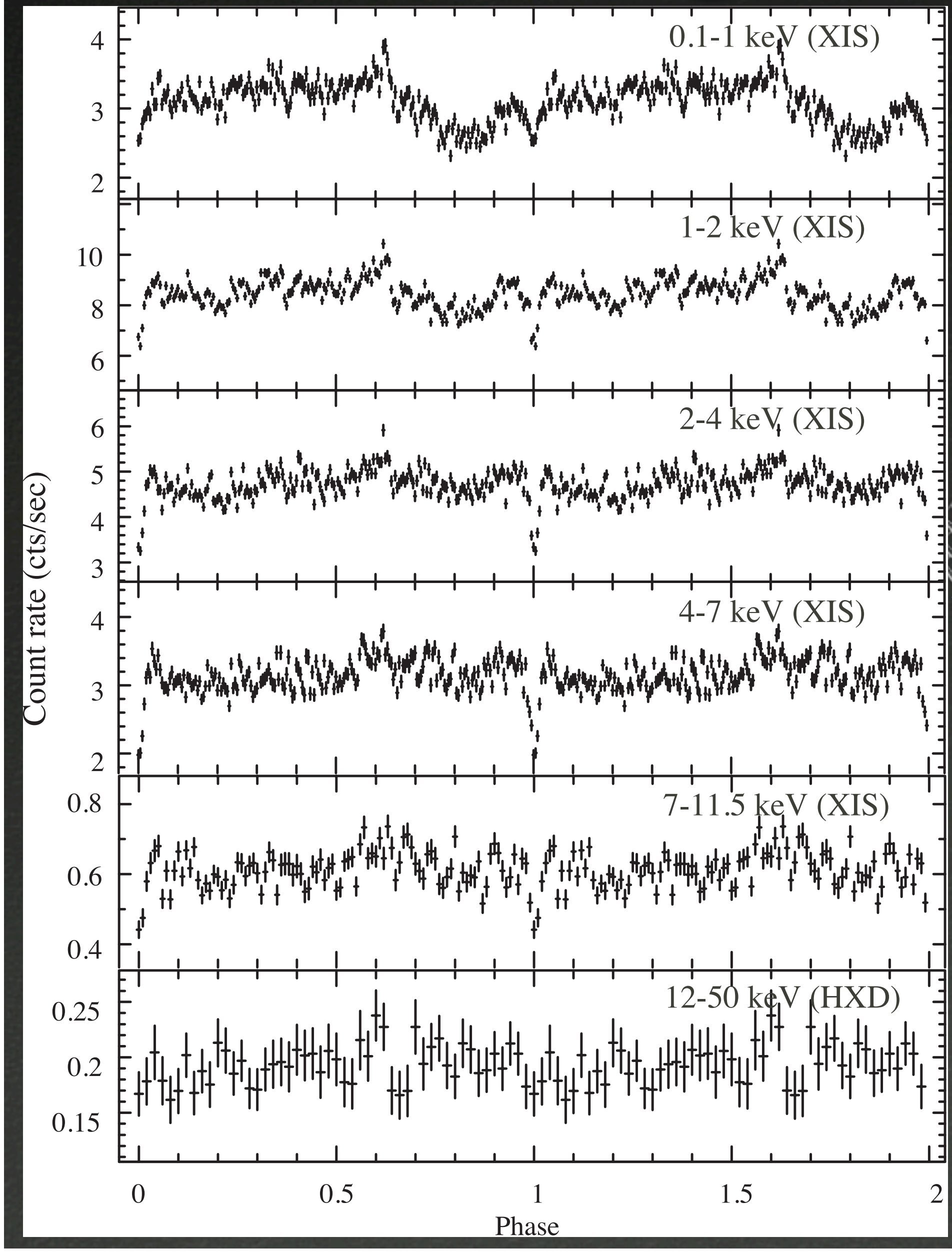
Variable synchronized with P_{spin}

•Spectra

XIS:101 ksec, HXD:59 ksec



Folded light curve with P_{orb}



- Folded light curve with P_{orb} (Mumford 1967 ephemeris)

(Normalized with averaged intensity)

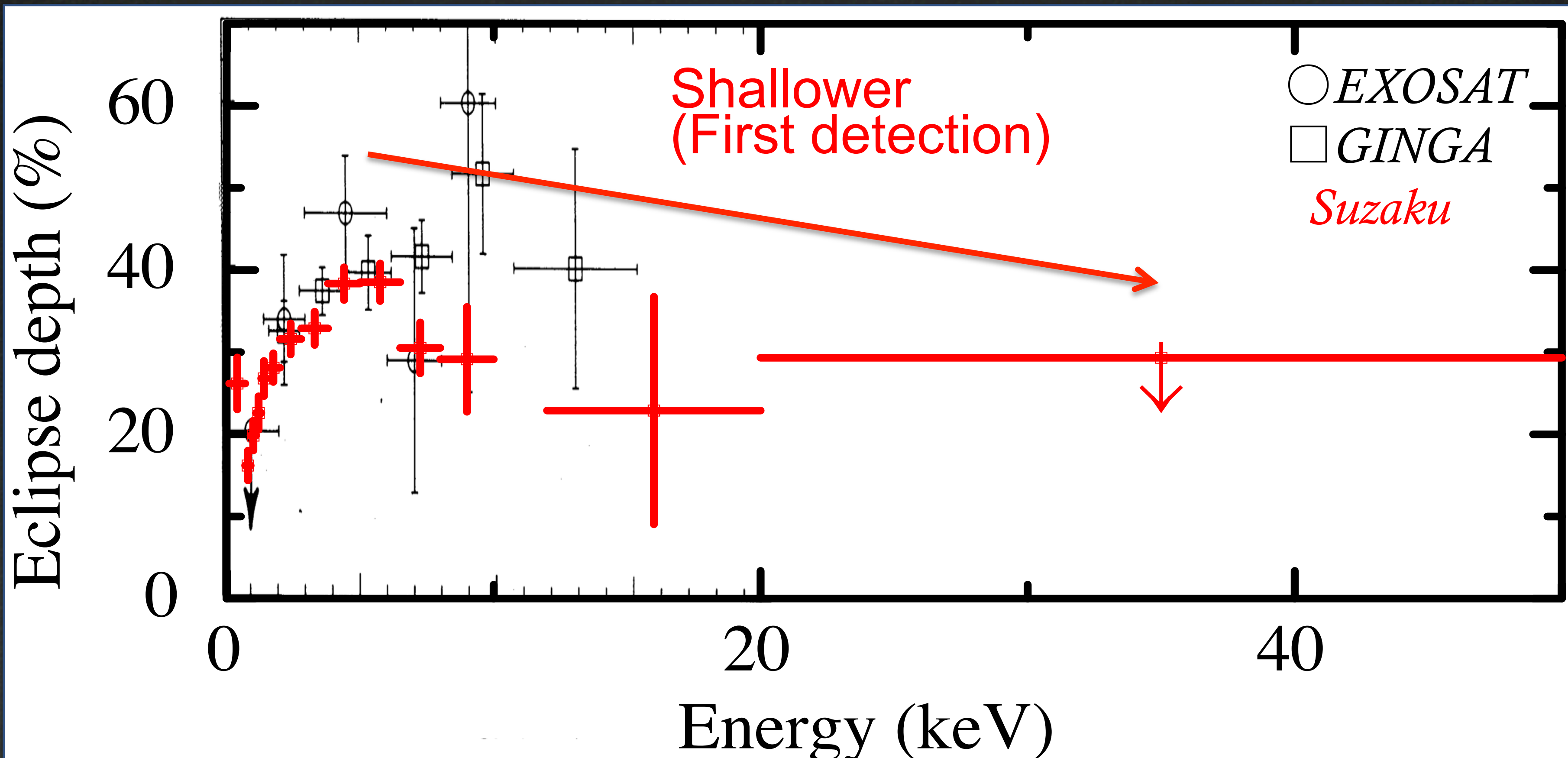
Deeper

Deeper?

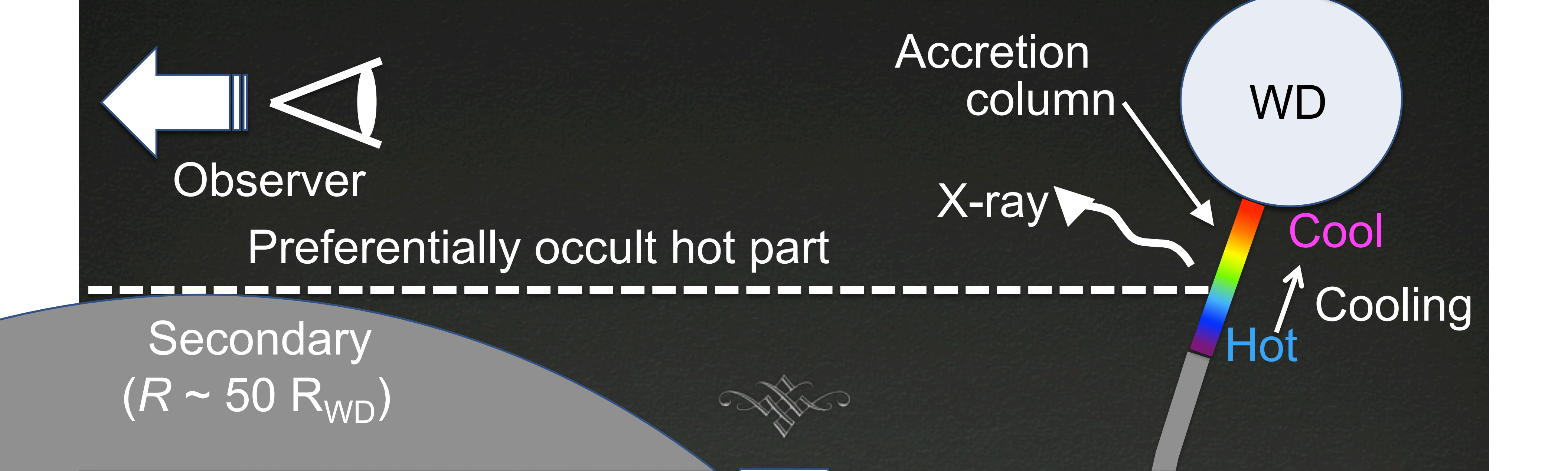
Seem to be shallower

Energy dependence of eclipse depth

- Energy vs Eclipse depth to average



Inconsistent with model



Monotonically deeper in higher enegy (Before Suzaku)

However,

Shallower above 7 keV (New) → Not consistent

EX Hya : low accretion → low density → weak cooling

→ Need re-examination of structure of accretion column

Standard accretion column

- Mass continuity equation

$$\frac{\mathrm{d}}{\mathrm{d}z}(\rho v) = 0 \Rightarrow \rho v = a$$

a : specific accretion rate
[g cm^{-2}s^{-1}]→key parameter

- Momentum equation

$$\frac{\mathrm{d}}{\mathrm{d}z}(\rho v^2 + P) = -\frac{GM_{\mathrm{wd}}}{z^2}\rho$$

- Energy equation

$$v\frac{\mathrm{d}P}{\mathrm{d}z} + \gamma P\frac{\mathrm{d}v}{\mathrm{d}z} = -(\gamma - 1)\Lambda$$

- Ideal-gas law

$$P = \frac{\rho k T}{\mu m_{\mathrm{H}}}$$

- Initial condition : free fall & strong shock (At top of accretion column)

$$v_0 = 0.25\sqrt{2GM_{\mathrm{WD}}/z_0},$$
$$\rho_0 = \frac{a}{v_0},$$
$$P_0 = 3av_0,$$
$$T_0 = 3\frac{\mu m_{\mathrm{H}}}{k}v_0^2.$$

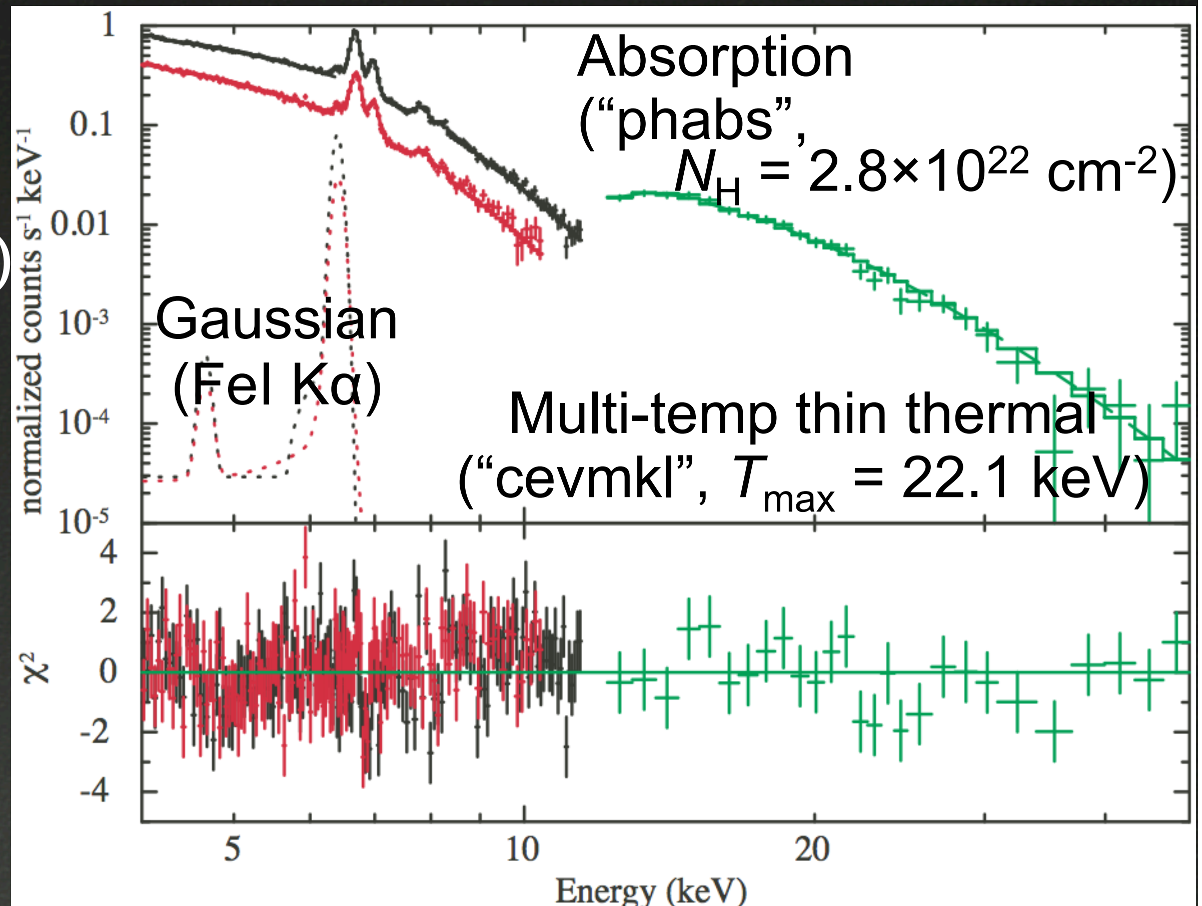
- Boundary condition : soft landing

$v = 0$ at WD surface

Cropper et al. (1999)
Suleimanov et al. (2005)

a of EX Hydrae

- Assumption
  - $M_{WD} = 0.79\ M_\odot$
  - $R_{WD} = 7.07\times10^8$ cm
  - $D = 64.5$ pc (Opt&IR)
  - $f = 0.01$ (Rosen et al. 1988)
  - f: fraction of accretion area



- Accretion rate

  Model fit →

  $L_{bol} = 2.2\times10^{32}$ ergs s^{-1}

$$L = \frac{GM_{WD}\dot{M}}{R_{WD}}$$

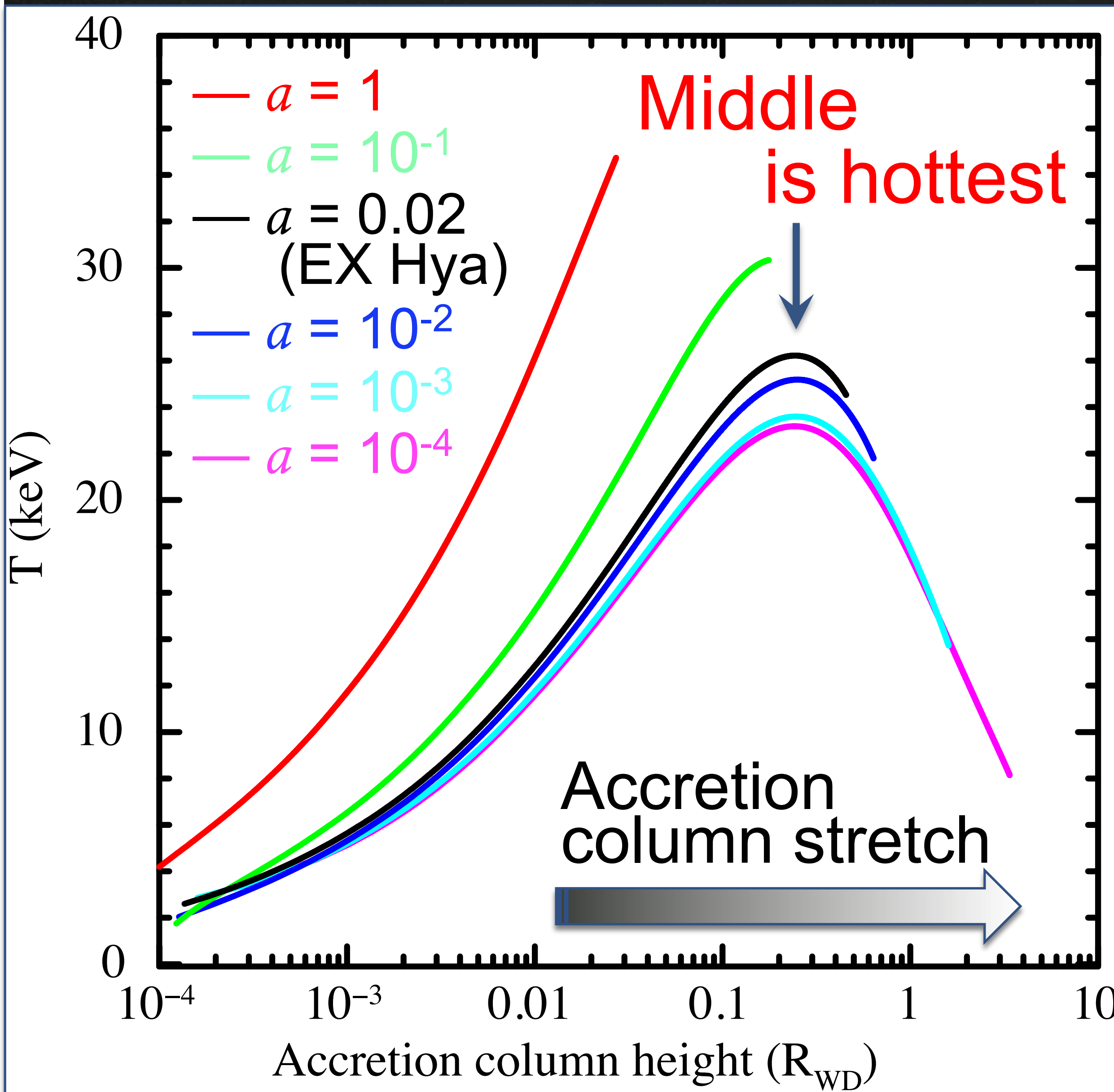
$\rightarrow \dot{M} = 1.6\times10^{15}$ g s^{-1}

- Specific accretion rate

$$\dot{M} = 4\pi R_{WD} a f$$

$\therefore a \sim 0.02$ g cm^{-2}s^{-1}

Accretion column with various *a*



- Accretion column temperature distribution

[assuming $M_{WD} = 0.79\ M_{\odot}$]

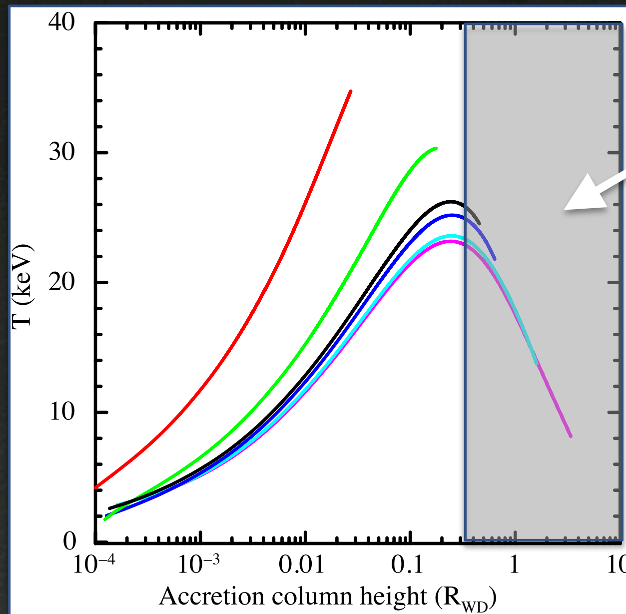
Smaller *a*

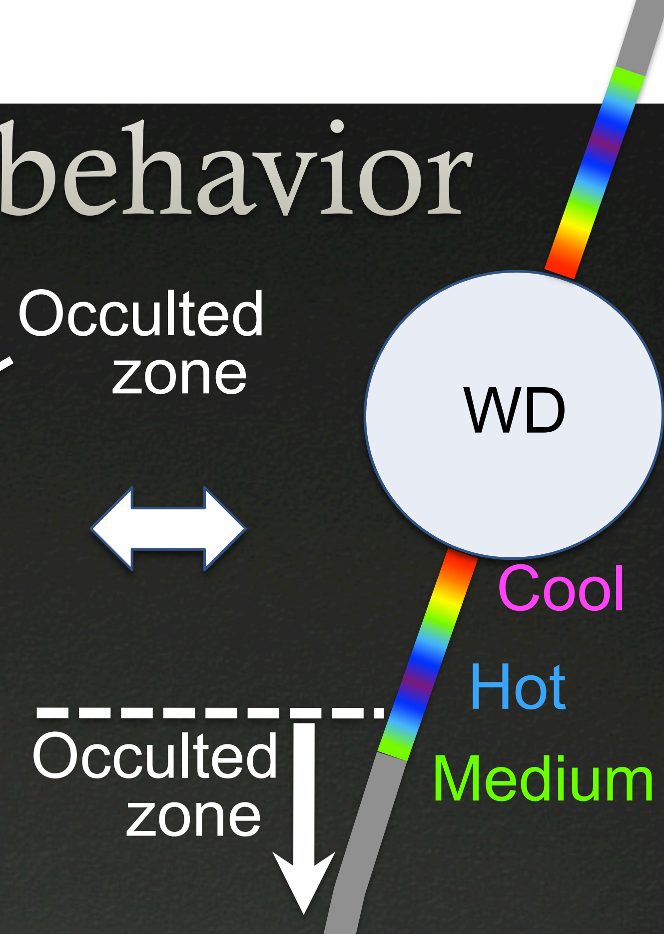
- → Weaker cooling
- → Longer time for complete cooling
- → Higher accretiom column

- → Energy input > Energy output
- → Hottest peak

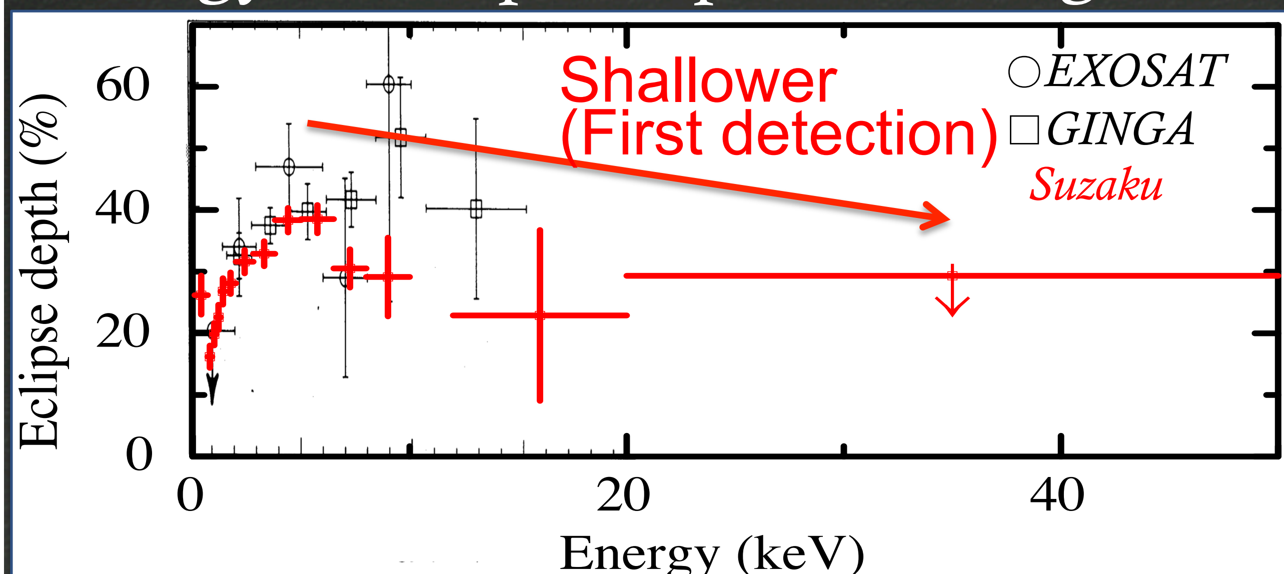
Cause of eclipse behavior

- Accretion column temperature distribution





- Energy vs Eclipse depth to average



Can explain by occultation of properly hot top of accretion column (*Qualitatively*)

Summary

- With Suzaku, we observed eclipsing IP EX Hydrae, which is very low accretion system.
- Eclipse in EX Hydrae is deeper in higher energy below 7 keV and shallower above 7 keV.
- Energy dependence of eclipse can not be explained by simple cooling accretion column.
- In low accretion rate IP including EX Hydrae, energy input overcomes cooling and the hottest peak emerge in the middle of accretion column.
- With occultation of properly hot top of accretion column, energy dependence of eclipse can be explained. (Qualitatively)

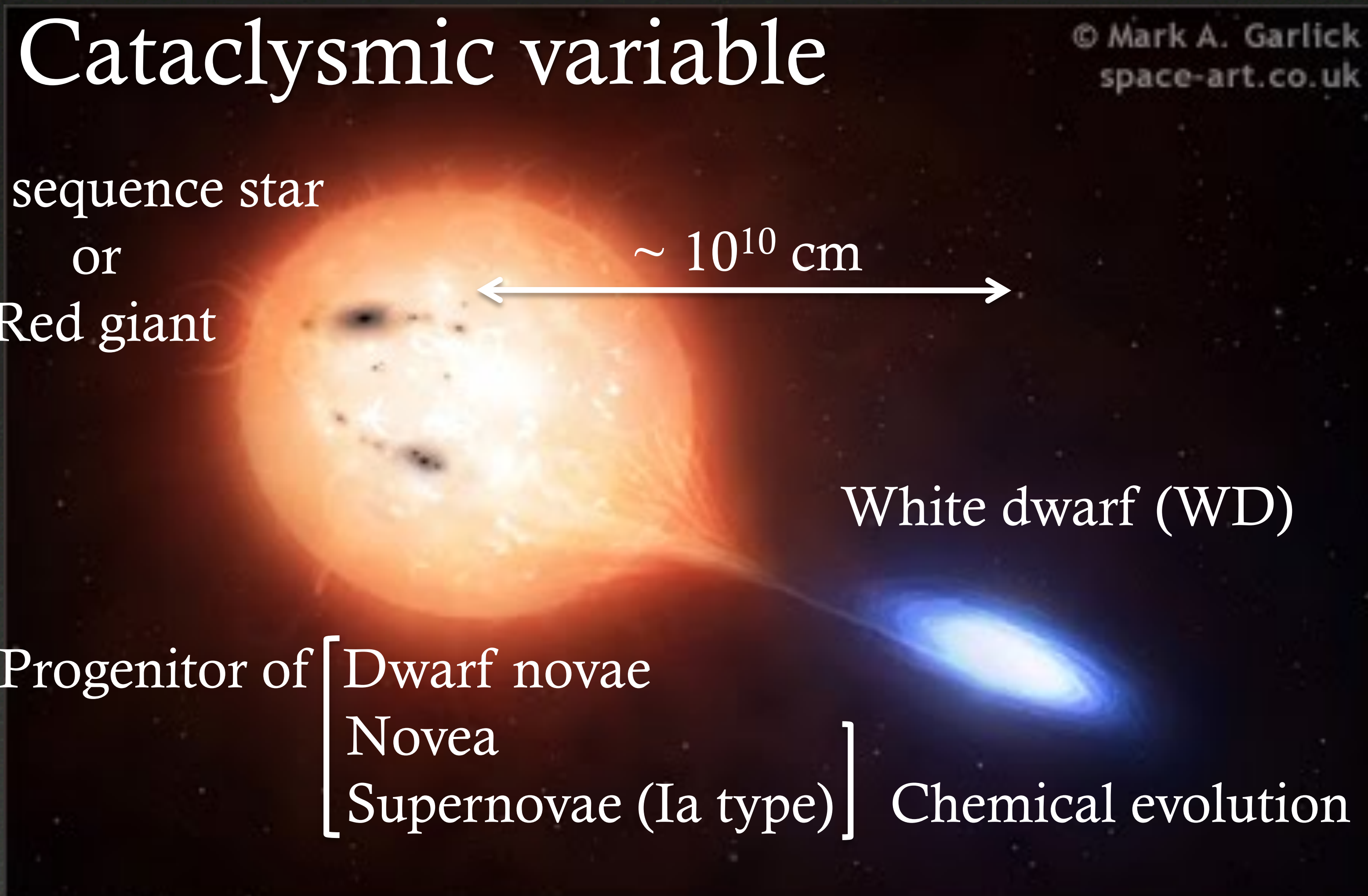
Introduction

Depth < 50% of average → occult only one pole

0.78±0.17 Mo (Hellier 1987)
0.4-0.7 Mo (Beuermann 2003)
0.91±0.05 Mo (Belle 2003)
0.5 Mo (Mhlahlo et al. 2009)

7.7e-11 at 1-10 keV (Suzaku, 2007)
1.3e-10 at 1-10 keV (Ginga, 1988)

Introduction



Source of [Galactic ridge X-ray emission (Yuasa et al. 2010)
Cosmic ray (Terada et al. 2008)

Possibility of non-equibilium

Low density → Non-equibiliumn ?

(At top of accretion column)

$\left[\begin{array}{l} nt_{\text{i-e}} \sim 3\times10^{11}\ \text{s cm}^{-3} \\ nt_{\text{ion}} \sim 1\times10^{12}\ \text{s cm}^{-3} \end{array} \right.$ (Masai 1984)

n:density

$t_{\text{i-e}}$: electron-proton equibilium time scale

t_{ion}: ionization equibilium time scale

$\rho = 1.6\times10^{14}\ \text{cm}^{-3}$

→ $\left[\begin{array}{l} t_{\text{i-e}} \sim 2\times10^{-3}\ \text{s} \\ t_{\text{ion}} \sim 5\times10^{-3}\ \text{s} \end{array} \right]$ → instant equilibrium

Free fall velocity ~ 5×10^{3} km s^{-1}

→non-equibilium region of accretion column

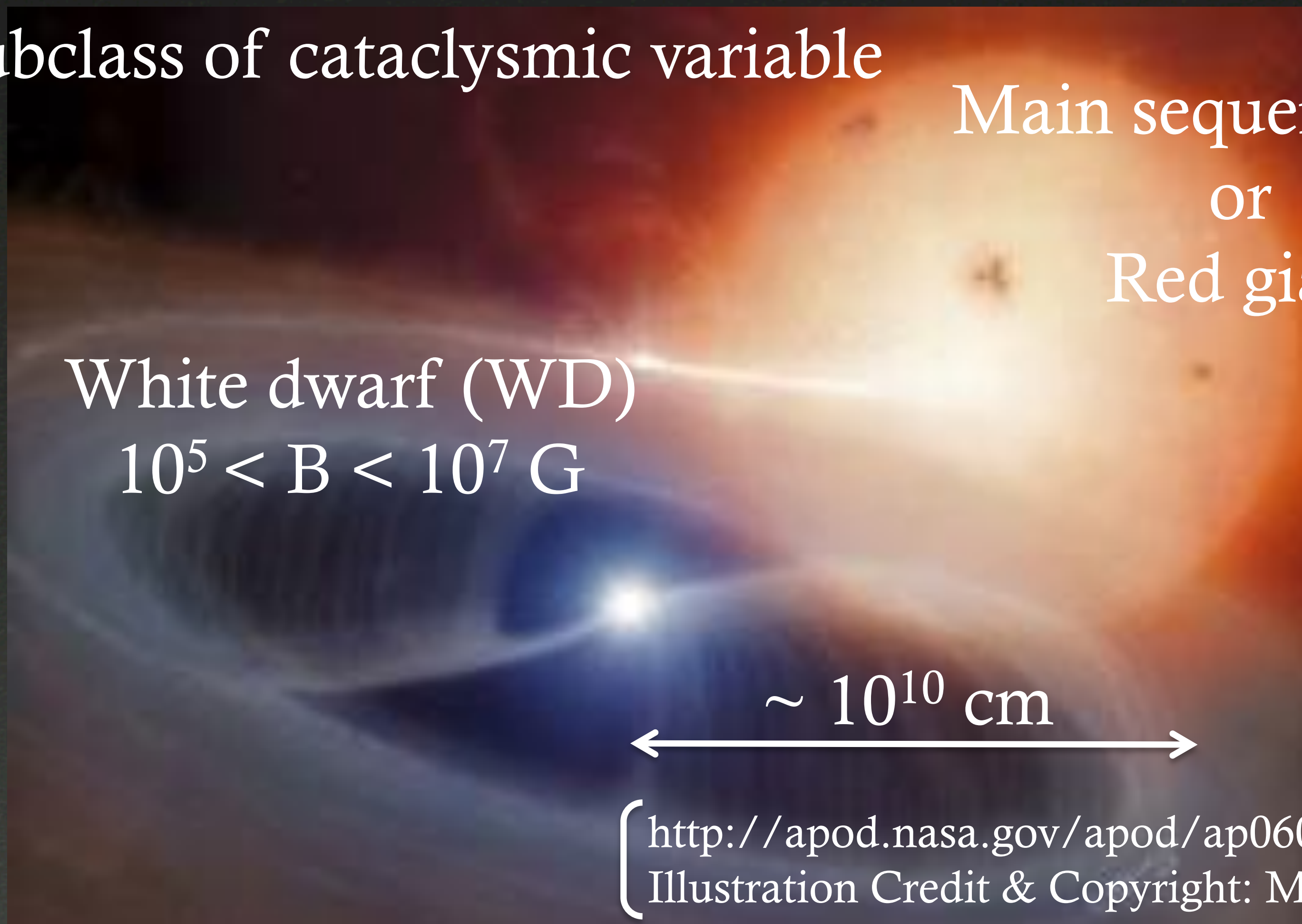
< 5 km < 0.1% of R_{WD}

(even if less density by 1 order → 1% of R_{WD})

→ Can not explain

Intermediate Polar (IP)

IP : Subclass of cataclysmic variable



http://apod.nasa.gov/apod/ap060521.html

Source of
- Cosmic ray (Terada et al. 2008)
- Galactic ridge X-ray emission (Yuasa et al. 2010)

Accretion column in EX Hya

a = 1 g cm^{-2}s^{-1}
[Suleimanov et al. 2005
Yuasa et al. 2010]

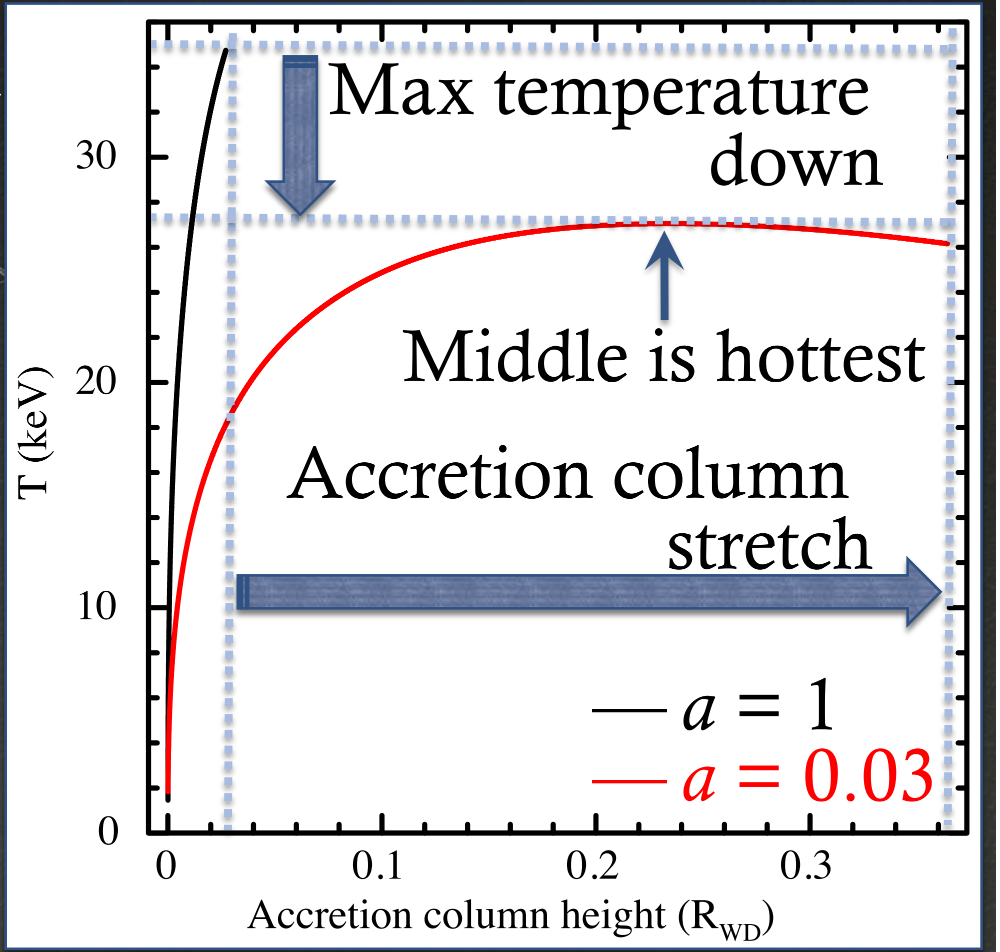
$$\dot{M} = 4\pi R_{\rm WD}^2 a f$$

EX HYA : a ~ 0.03 g cm^{-2}s^{-1}
(assuming [f = 0.002, $M_{\rm WD}$ = 0.79 Mo])

Low density → Weak cooling
- → Need longer time to release energy
- → Accretion column stretch
- → Max temperature down
- → Underestimation of $M_{\rm WD}$

- → Enegy input overcome energy output
- → Middle of accretion column is hottest

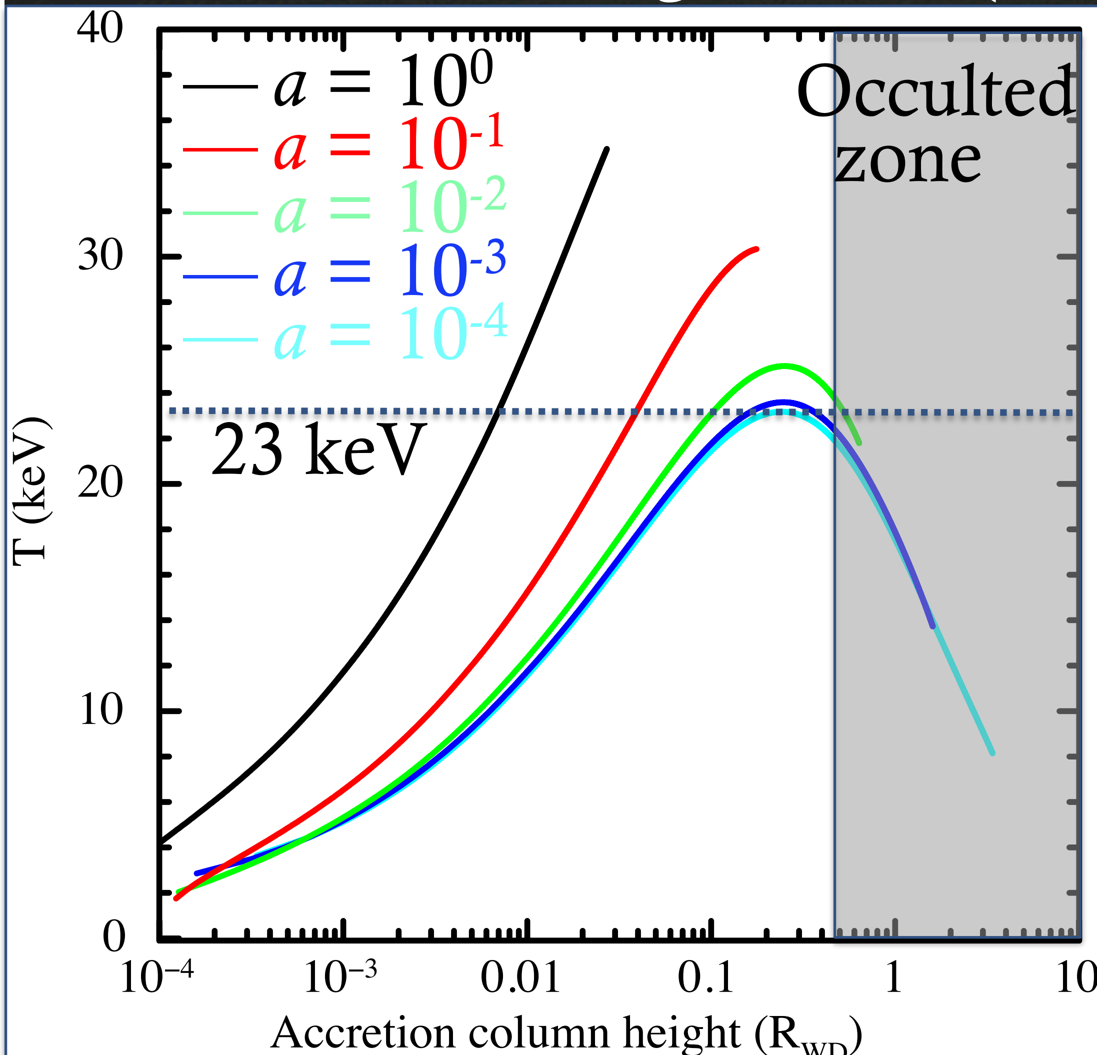
Accretion column temperature distribution
a = 1 vs a = 0.03



Accretion column with various *a*

Accretion column temperature distribution with

$a = 10^{(0, -1, -2, -3, -4)}$ g cm^{-2}s^{-1} (assuming M_{WD} = 0.79 Mo)



$a < 0.1$, hottest peak emerge in middle column

If properly hot column top is occulted

→ Energy dependence of eclipse depth (qualitatively)

Max temperature down to 23 keV

→ M_{WD} underestimated to 0.6 Mo

(Under assumption that Shock close to WD)

Possibility of non-equibilium

Low density → Non-equilibrium ?

(At top of accretion column)

$nt_{\text{i-e}} \sim 3\times10^{11}$ s cm^{-3} (Masai 1984)

[n : number density
$t_{\text{i-e}}$: electron-proton equilibrium time scale

$\rho = 1.6\times10^{14}$ cm^{-3}

→ $t_{\text{i-e}} \sim 2\times10^{-3}$ s → instant equilibrium

Free fall velocity ~ 5×10^{3} km s^{-1}

(with M_{WD} = 0.79 Mo, R_{WD} = 7.35×10^{8} cm)

→non-equibilium region of accretion column

~ 1 km < 0.1% of R_{WD}

(even if less density by 1 order → 1% of R_{WD})

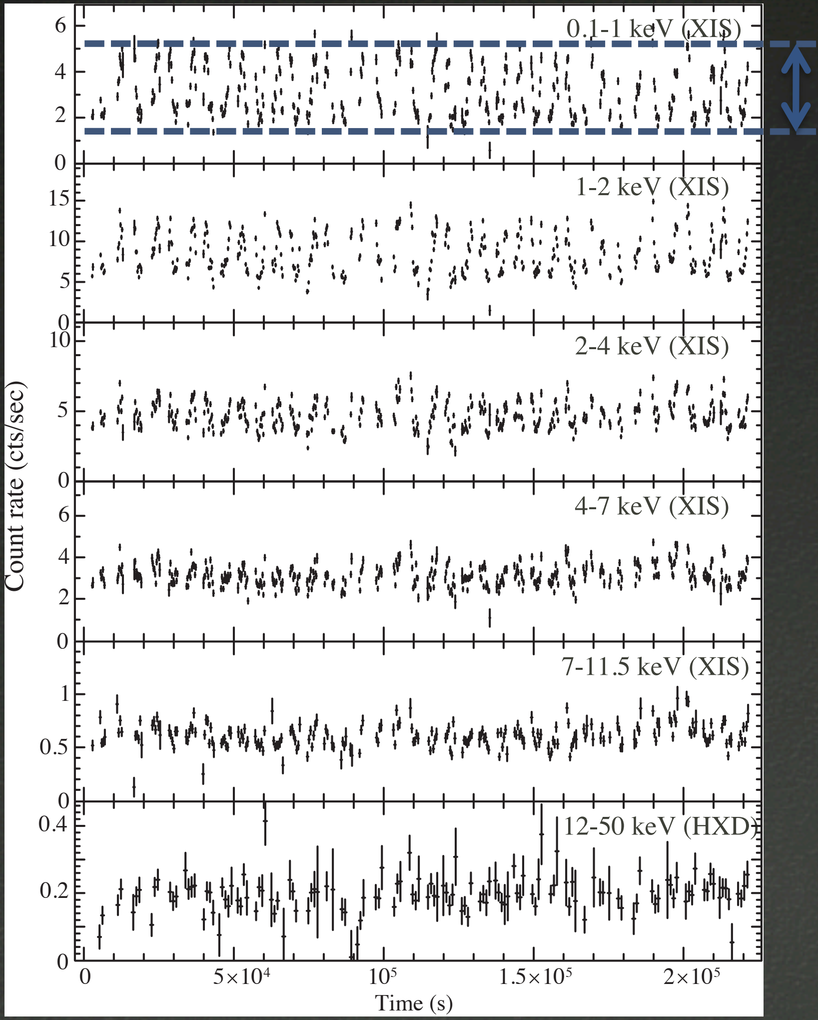
→ No major change of accretion column structure

i.e. almost simple cooling flow

Suzaku observation

2007 Jul 18th-21th

- Normalized light curve

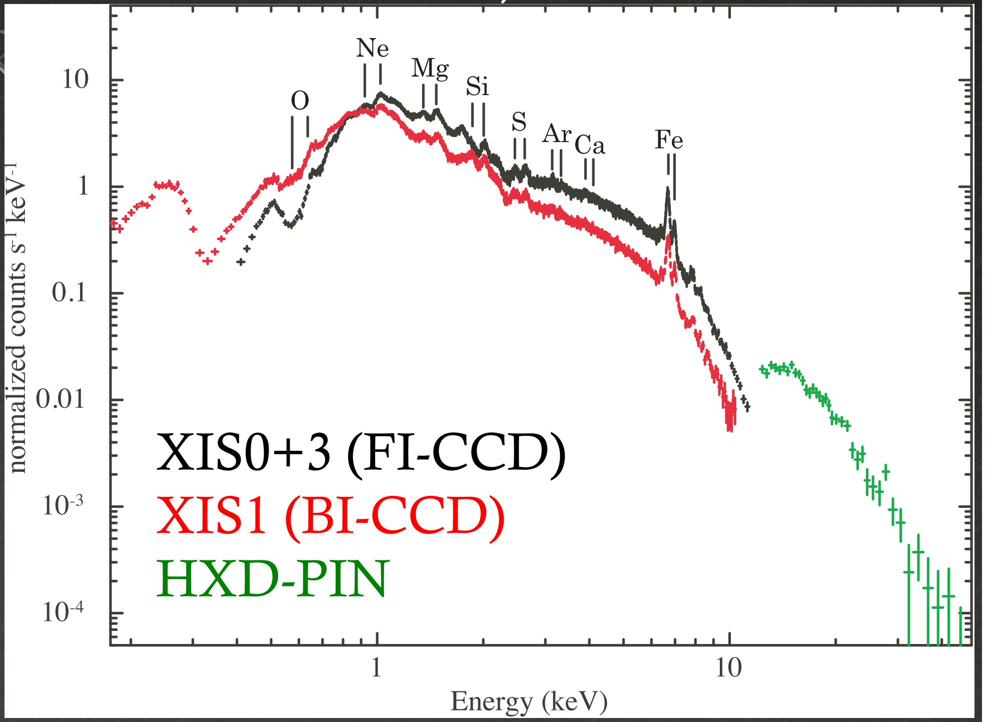


Variable synchronized with P_{spin}

- Absorption by pre-shock gas
- Occultation by WD

- Spectra

XIS:101 ksec, HXD:59 ksec



What is wrong?

- Geomery of eclipse?

    Deeper eclipse in intense WD spin phase (Obsevation)

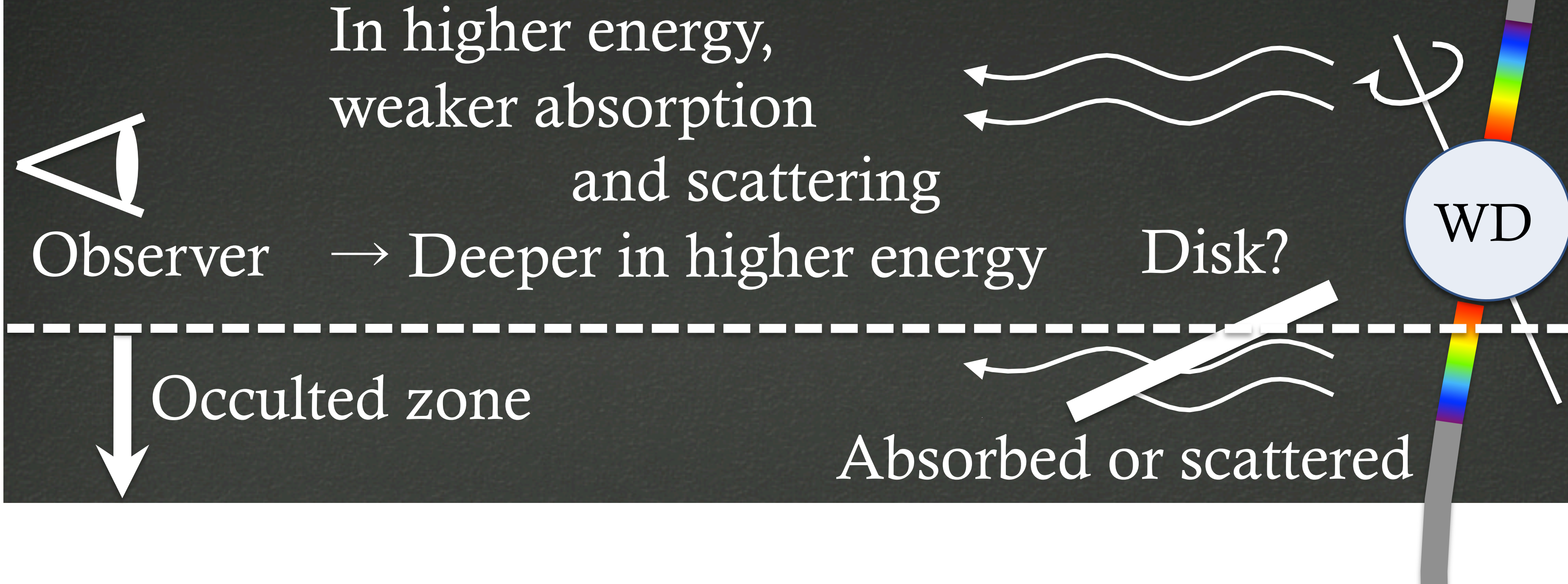
    → Agree with accretion curtain model (Rosen et al. 1988)

    which is widely accepted → Natural

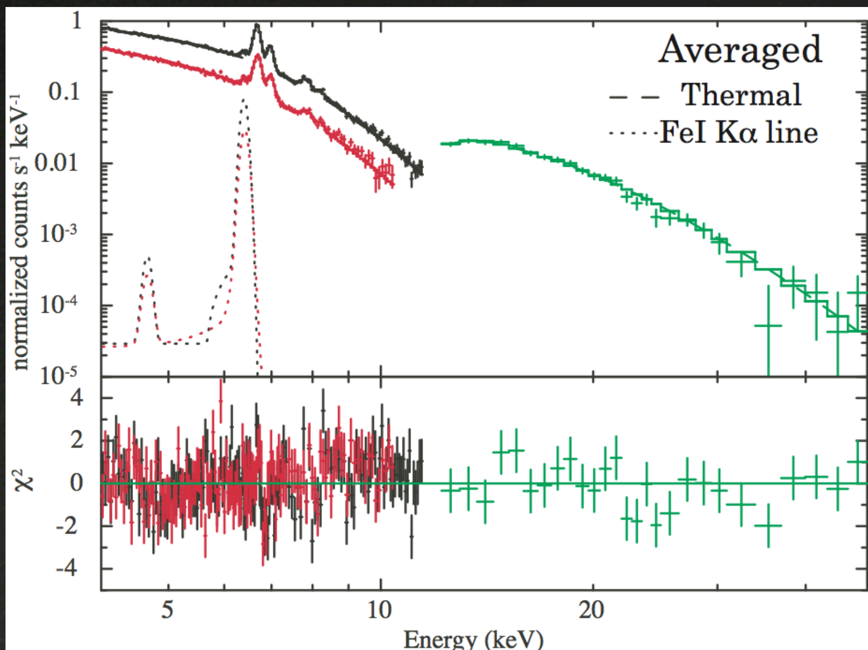
- Lack of extra absorption or scattering of occulted X-ray?

    → Monotonically deeper in higher energy

    → No need



Density of accretion column



Model fit (phenomenally) :

Photoelectric absorption
($N_H = 2.8\times10^{22}$ cm^{-2})

+

Multi-temperature thin thermal plasma (T_{max} = 21.1 keV)

+

Gaussian (Fluorescent Fe K α)

Assuming M_{WD} = 0.79 Mo, $R_{WD} = 7.35\times10^8$ cm (Opt&IR)

$L_{0.1-100} = 5.9 \times 10^{31}$ erg s^{-1}

$\rightarrow \dot{M} = 4.14 \times 10^{14}$ g s^{-1}

Post-shock plasma velocity

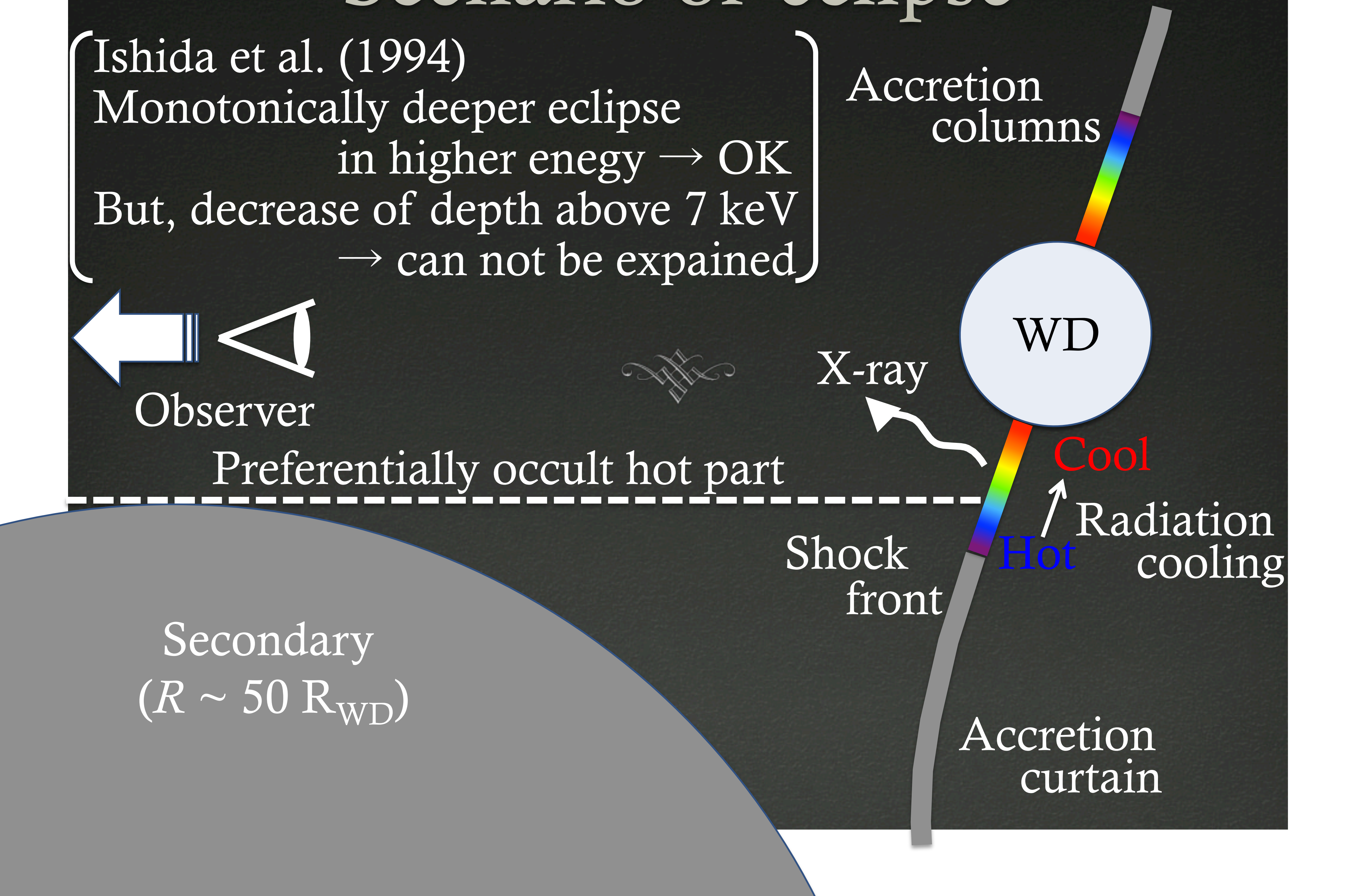
$$v_s = \frac{1}{4}\sqrt{\frac{2GM_{WD}}{R_{WD}}} = 1.36\times10^3 \text{ km s}^{-1}$$

(f : fraction of accretion area
Using f = 0.002 of XY Ari
(Hellier et al. 1997))

$$\Rightarrow \rho_s = \frac{\dot{M}}{4\pi f R_{WD}^2 v_s} = 2.4\times10^{-10} \text{ g cm}^{-3} = 1.5\times10^{14} \text{ cm}^{-3}$$

Scenario of eclipse

Ishida et al. (1994)
Monotonically deeper eclipse
in higher enegy → OK
But, decrease of depth above 7 keV
→ can not be expained



What is wrong?

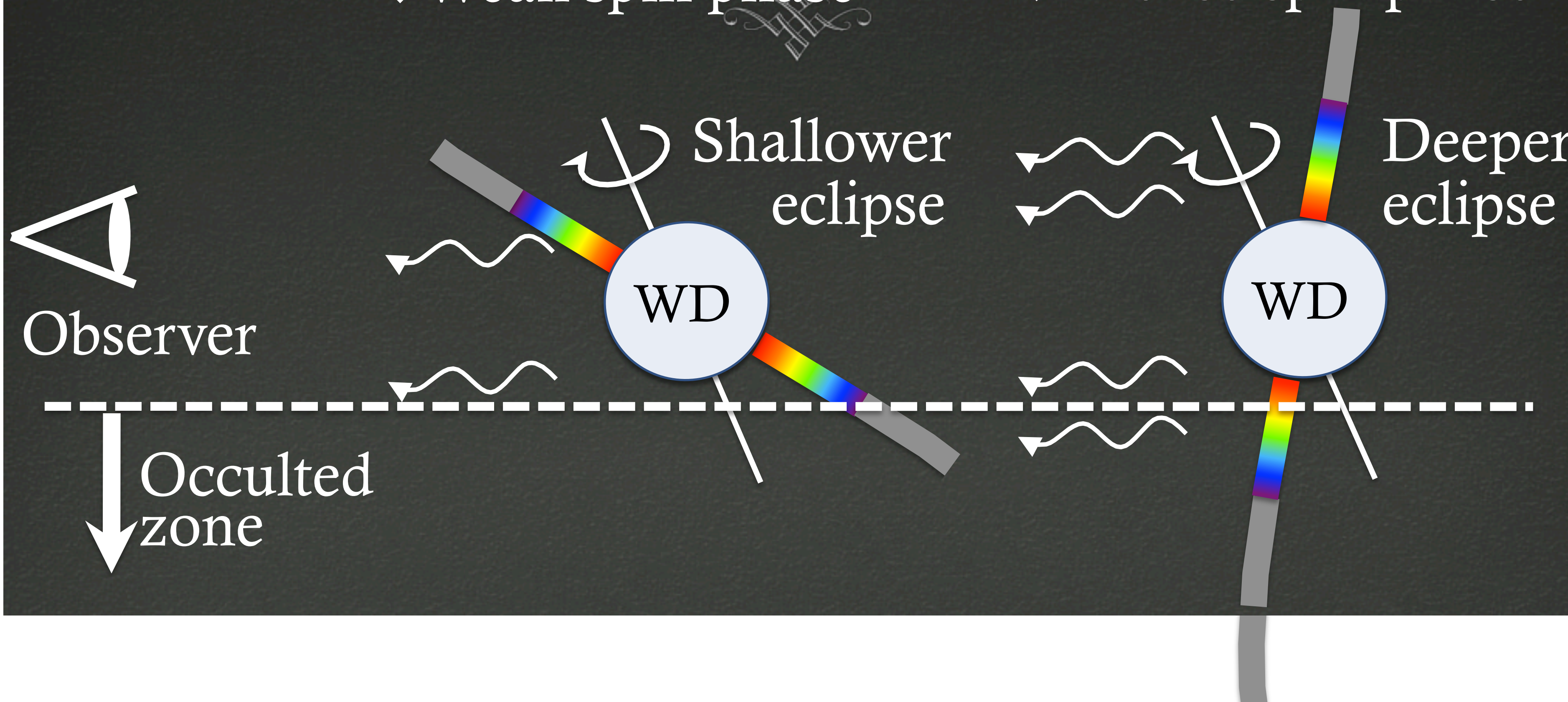
•Geomery of eclipse?

Deeper eclipse in intense WD spin phase (Obsevation)

→ Agree with accretion curtain model (Rosen et al. 1988)

which is widely accepted → Natural

◆Weak spin phase ◆Intense spin phase



What is wrong?

•Geomery of eclipse?

Deeper eclipse in intense WD spin phase (Obsevation)

→ Agree with accretion curtain model (Rosen et al. 1988)

which is widely accepted → Natural

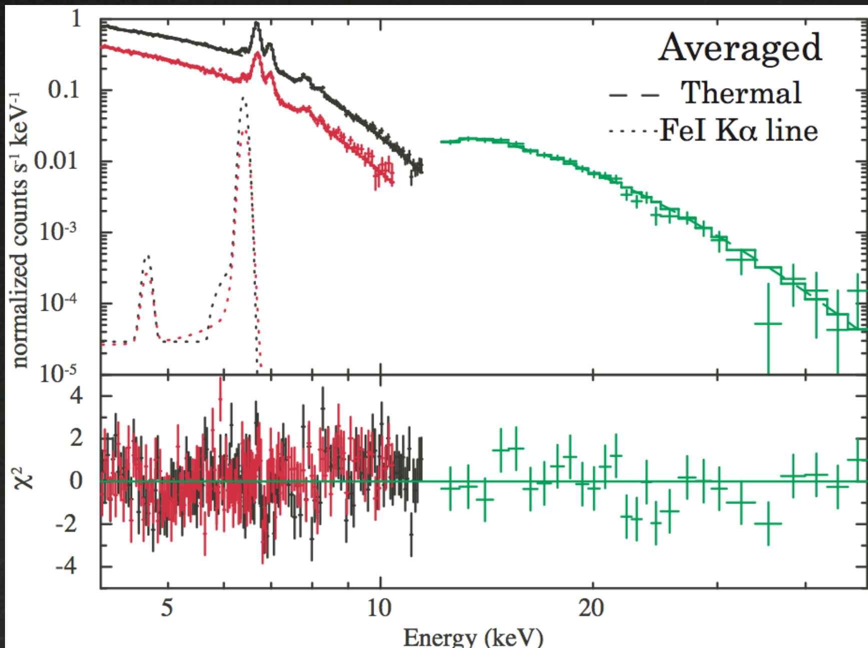
•Structure of accretion column?

EX Hya is low accretion system

→ low density → Weak cooling

→ Need re-examination

Density of accretion column



Model fit (phenomenally) :
Photoelectric absorption
(N_H = 2.8×10^{22} cm^{-2})
+
Multi-temperature thin thermal plasma (T_{max} = 21.1 keV)
+
Gaussian (Fluorescent Fe K α)

Assuming M_{WD} = 0.79 Mo, R_{WD} = 7.35×10^8 cm (Opt&IR)

$L_{0.1-100} = 5.9 \times 10^{31}$ erg s^{-1}

$\rightarrow \dot{M} = 4.14 \times 10^{14}$ g s^{-1}

Post-shock plasma velocity

$$v_s = \frac{1}{4}\sqrt{\frac{2GM_{WD}}{R_{WD}}}$$ =1.36×10^3 km s^{-1}

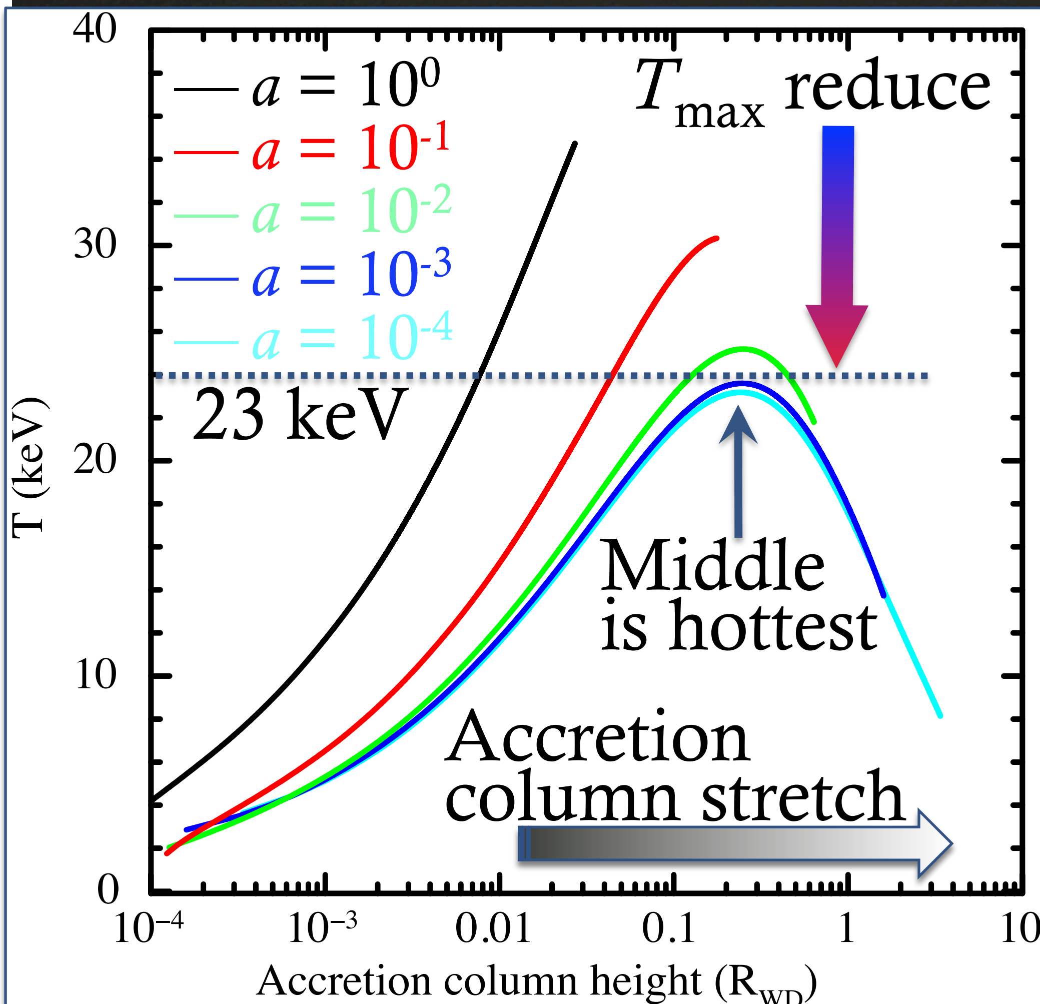
(f: fraction of accretion area
Using f = 0.002 of XY Ari
(Hellier et al. 1997))

$$\rho_s = \frac{\dot{M}}{4\pi f R_{WD}^2 v_s}$$ =1.6×10^{-10} g cm^{-3}

Accretion column with various a

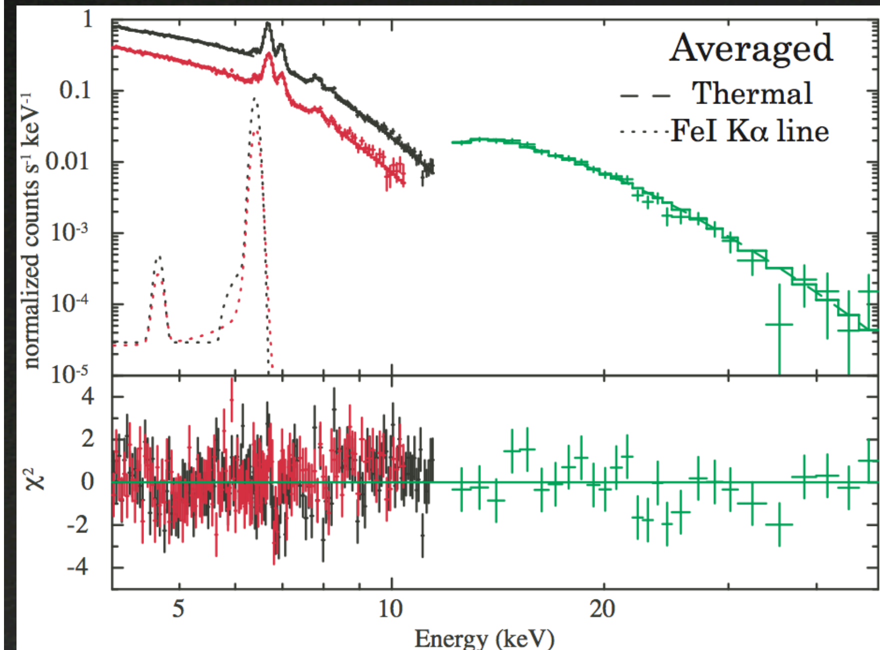
Accretion column temperature distribution with
$a = 10^{(0, -1, -2, -3, -4)}$ g cm^{-2}s^{-1} (assuming M_{WD} = 0.79 Mo)

$\dot{M} = 4\pi R_{WD}^2 a f$ →EX HYA: a ~ 0.03 g cm^{-2}s^{-1} (with f =0.002)



Low density
- →Need longer time for cooling
- →Accretion column stretch
- →Max temperature deduce to 23 keV
- →M_{WD} underestimated to 0.6 Mo
  (Under assumption that shock close to WD)
- →Enegy input overcome energy output (a < 0.1)
- →Middle of accretion column is hottest

Density of accretion column



Model fit :

Photoelectric absorption (N_H = 2.8×10^{22} cm^{-2})

+

Multi-temperature thin thermal plasma (T_{max} = 21.1 keV)

+

Gaussian (Fluorescent Fe K α)

Assuming M_{WD} = 0.79 Mo, R_{WD} = 7.35×10^8 cm (Opt&IR)

$L_{0.1-100} = 5.9 \times 10^{31}$ erg s^{-1}

$\rightarrow \dot{M} = 4.14 \times 10^{14}$ g s^{-1}

Post-shock plasma velocity

$$v_s = \frac{1}{4}\sqrt{\frac{2GM_{WD}}{R_{WD}}}$$ =1.36×10^3 km s^{-1}

f : fraction of accretion area

Using f = 0.002

(Hellier et al. 1997)

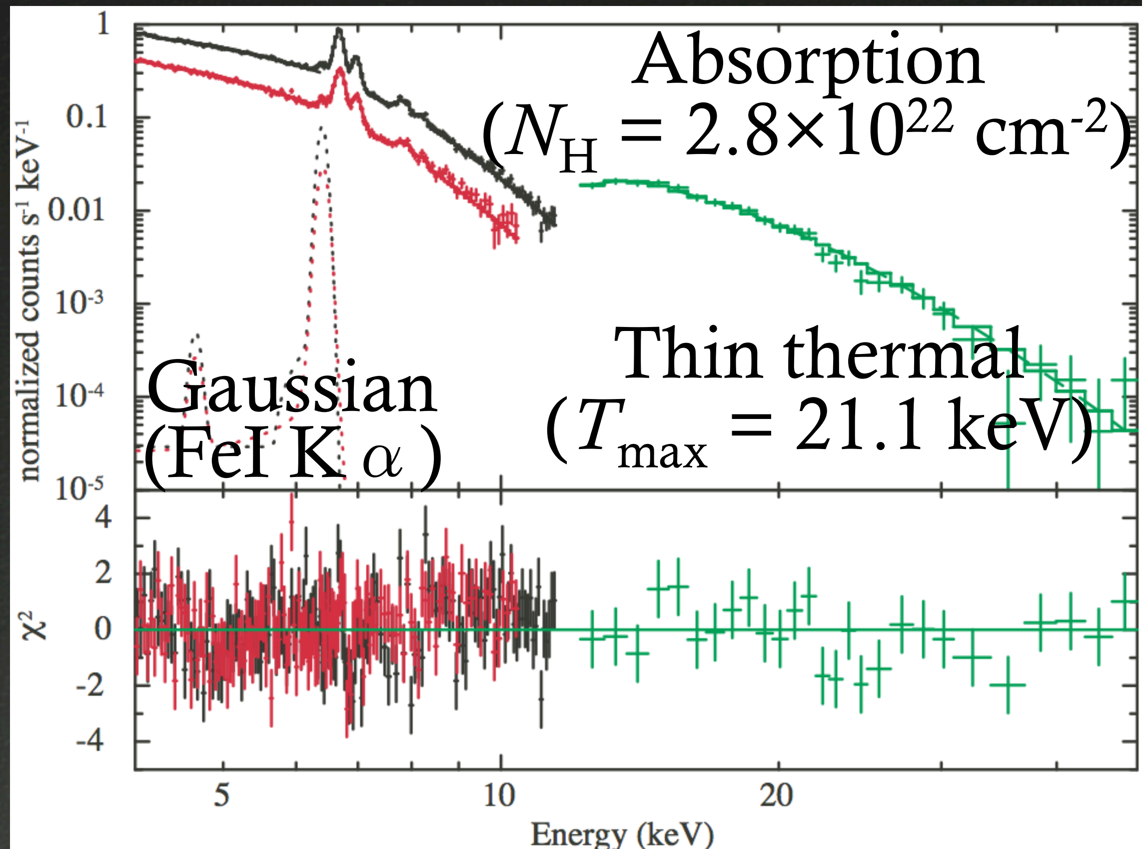
$$\rho_s = \frac{\dot{M}}{4\pi f R_{WD}^2 v_s}$$ =1.6×10^{-10} g cm^{-3}

Density of accretion column

- Density

$$\rho = \frac{\dot{M}}{4\pi f R_{WD}^2 \upsilon}$$

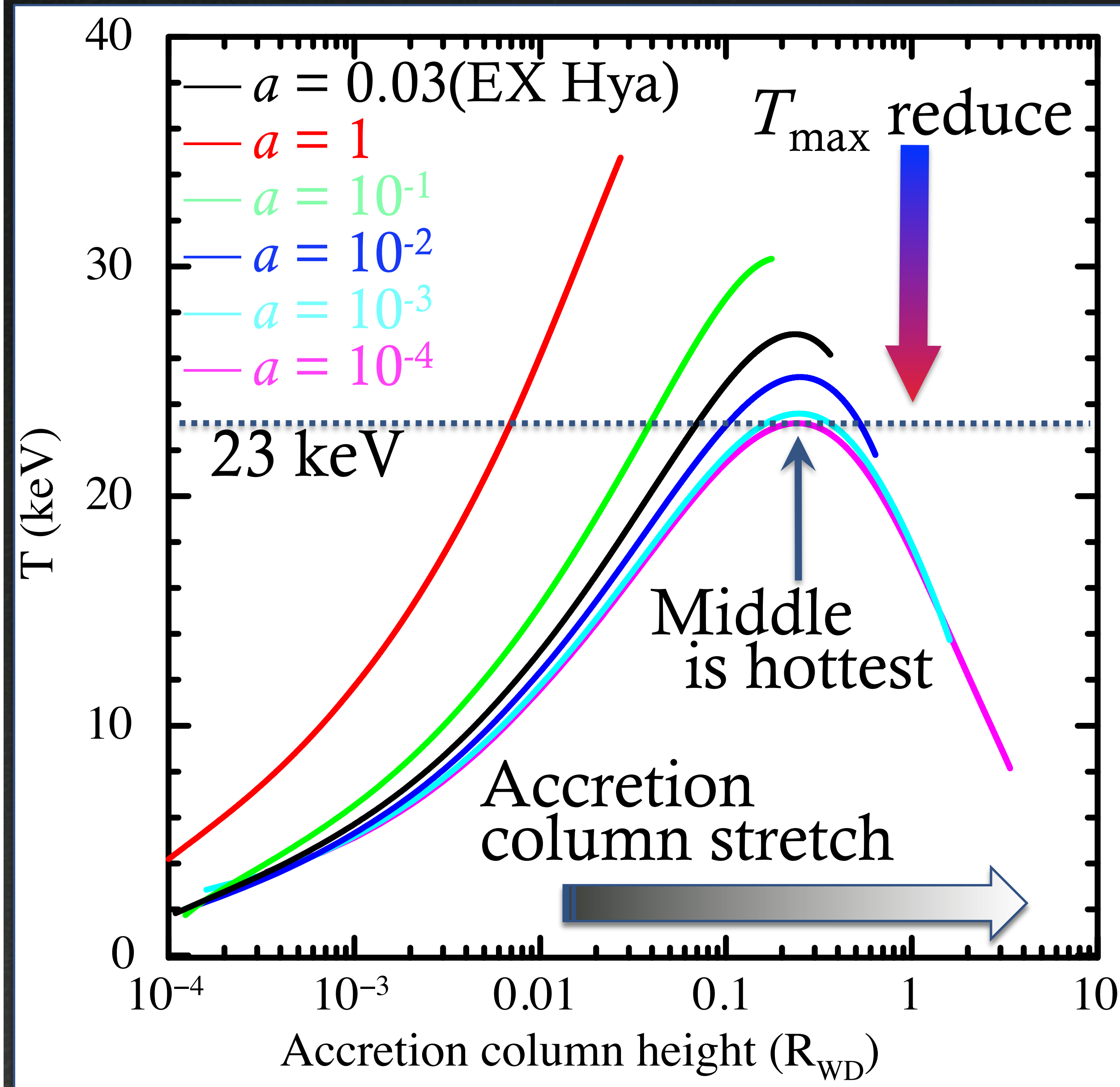
Assuming
$M_{\rm WD}$ = 0.79 Mo
$R_{\rm WD}$ = 7.35×10^8 cm
(Opt&IR)
f = 0.002
(Hellier et al. 1997)
f: fraction of accretion area



- Accretion rate : $L_{\rm bol}$ = 5.9×10^{31} ergs s^{-1} → $\dot{M}$ = 4.1×10^{14} g s^{-1}
- Plasma velocity : $\upsilon = \frac{1}{4}\sqrt{\frac{2GM_{WD}}{R_{WD}}}$ =1.4×10^3 km s^{-1}

$\therefore\ \rho$ =1.6×10^{-10} g cm^{-3}

Accretion column with various a



- Accretion column temperature distribution (assuming M_{WD} = 0.79 Mo)

$$\dot{M} = 4\pi R_{WD}^2 a f$$

⇩

EX HYA:

$a \sim 0.03$ g $cm^{-2}s^{-1}$

Underestimation of M_{WD}

0.79 (Original) → 0.6 Mo (23 keV)

Intermediate polar EX Hydrae

P_{spin} = 4022 sec (Mauche et al. 2009)
P_{orb} = 5895 sec (Mumford 1967)
D = 64.5 pc (Beuermann et al. 2003)
M_{WD} = 0.48 $M_{\odot}$ (X-ray line ratio, Fujimoto&Ishida 1997)
= 0.50 $M_{\odot}$ (X-ray, Yuasa et al. 2010)
= 0.79 $M_{\odot}$ (Opt&IR, Beuermann & Reinsch 2008)

$L = 5.8\times10^{31}$ ergs sec^{-1} (Pekon & Balman 2010)

[cf. typical IP V1223 Sagittarii
: $L = 1.3\times10^{34}$ ergs sec^{-1} (Hayashi et al. 2011)
→ EX Hydrae is low accretion rate

X-ray partial eclipse
→ Occultaion of part of one accretion column
(Detail in next slide)
→I = 77.8 deg (Beuermann